

# Measuring transmission and forces from observatory equipment vibration

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## ABSTRACT

We describe measurements of both the vibration forces imparted by various types of observatory equipment, and the transmission of these forces through the soil, foundations and telescope pier. These are key uncertainties both in understanding how to mitigate vibration at existing observatories and for developing a vibration budget in the design of future observatories such as the Thirty Meter Telescope. Typical vibration surveys have measured only the resulting motion (acceleration); however, this depends on both the source and the system being excited (for example, isolating equipment results in less force being transmitted, but greater motion of the equipment itself). Instead, here we (a) apply a known force input to the pier from a shaker and measure the response at different locations, and (b) use isolator properties combined with measured acceleration to infer the forces applied by various equipment directly. The soil foundation and pier transmission can then be combined with a finite element model based vibration transmission analysis to estimate the optical consequences. Estimates of plausible source levels supports the development of a vibration budget for TMT that allocates allowable forces to the sources of vibration; this is described in a companion paper.

**Keywords:** TMT, Vibration, Extremely-Large-Telescopes, Subaru Observatory

## 1. INTRODUCTION

The Thirty Meter Telescope (TMT) has defined a vibration budget: an allocation for each piece of equipment or subsystem of how much force distributed over frequency can be imparted to the structure in order that the combined effect from all such sources meets the overall TMT error budget allocation of 30 nm residual AO-corrected wavefront error (including both image jitter and M1 segment motion).<sup>1</sup> This vibration budget is dependent on model-predicted sensitivity to force inputs, force transmission through the soil foundation and pier, and also on a realistic assessment of the achievable force levels for different equipment. We have conducted measurements using NRC Herzberg equipment<sup>2</sup> to better understand vibration transmission through the foundation and pier in particular (where we do not have reliable models), and to obtain representative estimates of the force levels that existing equipment produces.

A key uncertainty in estimating the transmission of vibration from sources to the resulting optical consequences is the transmissibility through the soil, for which we do not have model-based estimates. The response of the telescope structure itself can be obtained from a finite element model, but it is also valuable to validate these model-based results. We describe forced-response measurements of the frequency-dependent transfer function describing vibration propagation at Subaru Observatory. A shaker inside the telescope pier is used to introduce a known force, and the response measured at multiple locations including the Nasmyth platform, the base of the enclosure fixed wall, the top of the enclosure fixed wall, and the floor of the facilities building. Note that by reciprocity, these measurements also give the response at the telescope pier due to forcing at other locations, of particular interest for sources in the facilities building or on the enclosure. By introducing a force at a single frequency at a time, high signal-to-noise ratios can be achieved even for responses some distance away, and

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despite the background vibration spectrum from operating equipment. Since no equipment needs to be turned off, conducting this type of test also has minimal interference with on-going daytime activities at the observatory. In principle, this technique could also be used at nighttime to directly measure transfer functions from force at a given location to on-sky jitter using waverfront sensor data.

We also present an approach for measuring the force imparted to the mounting surface beneath isolation-mounted equipment. This is based on measuring the transfer function associated with the isolation, using this to estimate isolator characteristics (where otherwise unavailable), and combining this with the measured operating motion of the equipment to infer the force seen at the base of the isolator. We demonstrate this approach with a measurement of a cryocompressor at NRC Herzberg in Victoria, Canada. Based on further validation of the approach, we plan on measuring the vibration produced at operating observatories from isolation-mounted facility equipment such as chillers, pumps, air handlers and hydrostatic bearing systems.

The same technique can also be used for sources of vibration mounted to the telescope, such as cryocoolers or flow-induced vibration from pipes carrying coolant. In these cases however the measurements cannot be easily done in situ for a variety of reasons. Telescope mounted equipment is often either poorly isolated or not isolated at all. Even in cases where isolation is used the dominant source of motion at all frequencies may not only be on the equipment side of the isolation making it difficult to determine the net effect of the isolation and consequently the force transmitted. It may be more practical to develop force estimates for telescope mounted sources using representative test fixtures in the laboratory as has been previously done for cryocoolers by Jakob and Lizon.<sup>3</sup> Test fixtures for measuring flow-induced vibration forces from representative fluid piping can also be envisaged.

Using a variety of such techniques, we plan to establish initial estimates of plausible source levels to (i) assess whether the overall error budget allocation to equipment vibration can be met, (ii) inform design decisions, such as source locations, types of cryocoolers used at instruments, or isolation requirements and (iii) ensure that cost-effective trades can be made between mitigation strategies when vibration sources exceed their allocations.

In addition to its value in designing TMT or other future observatories to meet performance requirements in a cost-effective manner, the transmission and force information is also useful for understanding vibration at existing observatories and thus how to improve it.

## 2. METHODOLOGY

### 2.1 Measuring vibration transmission through soil/pier

For measuring the response to forces inputs, we use a modal exciter mounted to a table, as shown in Figure 1 and schematically in Figure 2. The stinger from the exciter is attached to an isolated mass. Note that if the stinger were attached to the floor directly, then Newton's second law would simply mean that we would put a force into the floor through the stinger and an equal and opposite force into the floor through the feet of the table. The isolation thus reduces one of these forces above the isolator frequency – with  $m = 56 \text{ kg}$ ,  $k = 2.7 \times 10^4 \text{ N/m}$ , this is roughly 3.5 Hz. Above this frequency the shaker force is thus effectively applied to the ground only through the feet of the table. An accelerometer and a load cell at the end of the stinger measure the motion of the mass and the force applied to the mass; at frequencies well above the isolator frequency the measured force will be the approximately same magnitude as the force transmitted to the floor through the feet of the table. Closer to the isolator frequency, the force transmitted through the springs of the isolator needs to be accounted for, but this is straightforward to compute from either the load cell or the accelerometer on the stinger: the net force is related to the measured force  $F_m$  and measured acceleration  $a_m$  as

$$\frac{F_{\text{net}}}{F_m} = \frac{ms^2}{ms^2 + k} \quad F_{\text{net}} = ma_m$$

Seismic accelerometers are placed at various locations throughout the observatory to measure the transfer function from the shaker force. We use a single-frequency sinusoidal input at various selected frequencies, and look for the accelerometer response at the same frequency. This has three main advantages relative to a broadband excitation. First, by choosing the input frequencies carefully we can avoid exciting at the same frequency as existing equipment and thus obtain good signal to noise without having to turn equipment off. Second, we can obtain any desired signal to noise ratio (SNR) simply by averaging over a long enough period of time (within reasonable limits); e.g. the 4-minute data record used in testing at Subaru yields frequency resolution of 0.0042 Hz, and only the background noise within this narrow band about the drive frequency affects



Figure 1. Modal exciter test setup, showing exciter (black, centre), the table to which it is mounted, and the isolated mass under table driven vertically by the stinger of the exciter. A nearby accelerometer on the floor is visible in the foreground.

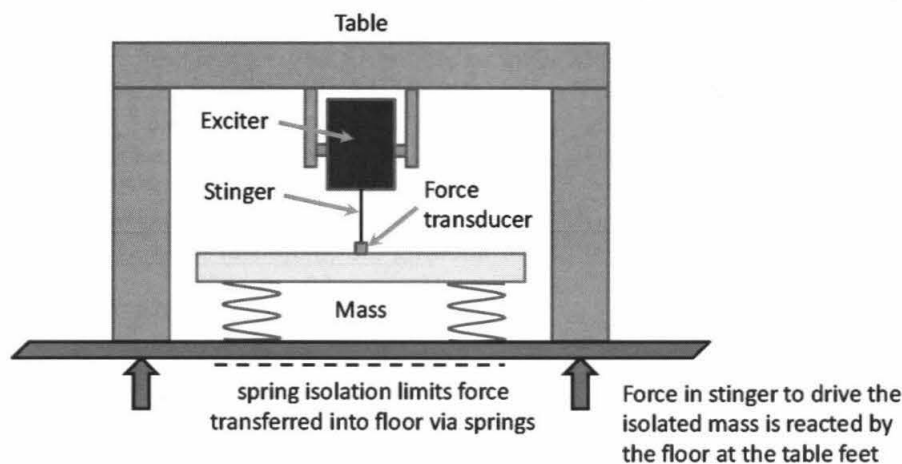


Figure 2. Schematic of test setup, showing reaction forces transmitted through the feet of the table. The mass is  $m = 56$  kg, and the combined spring constant of the three springs is  $k = 2.7 \times 10^4$  N/m; the force transmitted across the springs is negligible at the frequencies used here.

SNR; see Fig. 5. And third, since we aren't concerned about the phase of the transfer function, we can obtain the response transfer function from any measurement location without the need for cables between the two; that is, we don't need synchronous recording of the input and output signals on the same data acquisition system. The drawback to using sinusoidal excitation is that we only get information at discrete frequencies. This is adequate for understanding non-resonant vibration transmission through the ground. However, this is a potential limitation of the approach for understanding transfer functions on the telescope itself where the presence of lightly-damped structural resonances means that the transfer function between input and output may be highly frequency-dependent (see [1] for model-based examples).

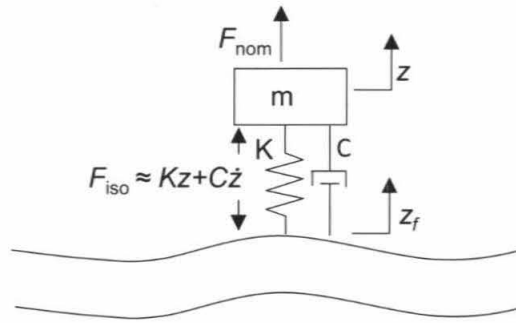


Figure 3. Sketch of single-point isolation mount (equipment mounted at 4 corners will introduce tip and tilt modes as well, but the same picture is applicable for the “piston” motion). The applied force to the mass (e.g. due to rotating machinery imbalance) yields motion  $z = F_a / (ms^2 + Cs + K)$ , where  $s$  is the Laplace variable  $s = 2\pi if$ . The force transmitted to the floor is  $F_f = (K + Cs)z$  assuming that the floor motion is small compared to the equipment motion (i.e. the transmitted force is reduced above the resonant frequency of the system). The motion  $z$  of the equipment can thus be used to compute the force transmitted to the floor provided that the isolator spring constant and damping are known.

## 2.2 Measuring Force from Vibrating Equipment

For any equipment that is mounted on isolators where the dominant motion is on the equipment side of the isolators, the force input through the isolators can be estimated from the motion of the equipment itself and from the isolator properties; see Figure 3. The former can readily be measured using accelerometers. The latter can either be obtained directly from the manufacturer or through measurement. A direct measurement can be made either (i) with a known weight and a displacement gauge to obtain the stiffness or (ii) using an impact hammer and accelerometer to obtain the dynamic response, from which both the stiffness and the damping can be obtained. The dynamic approach is in principle preferable in that the force transmitted through the isolator depends on isolator damping as well as stiffness, however, in some cases it can be difficult to obtain accurate estimates of isolator properties while the equipment is running. In either case, ideally the piston, tip, and tilt degrees of freedom all need to be estimated in order to obtain the net isolator properties in the vertical (piston) direction (that is, the measurement needs to be made at 3 corners of the equipment). Also note that the dynamic approach can be used even with non-vertical mounting, e.g. on isolated fluid lines.

Figure 3 illustrates the dynamics of an isolator. Assuming the floor motion is small compared to the equipment motion, then the force transmitted through the isolator ( $F_{iso}$ ) at frequency  $f$  can be estimated from the measured equipment displacement  $z$  and the isolator stiffness  $K$  and damping  $C$ ; the force that would have been transmitted if there had been no isolation can also be estimated knowing the equipment mass  $M$

$$F_{iso} = (K + Cs)z \quad F_{nom} = Ms^2z \quad \frac{F_{iso}}{F_{nom}} \simeq \left( \frac{f_{iso}}{f} \right)^2 \quad (1)$$

where the ratio  $F_{iso}/F_{nom}$  above is valid at frequencies well above the isolation resonance  $f_{iso} = (2\pi)^{-1} \sqrt{K/M}$  assuming the damping  $C$  is small.

For equipment that is not isolated, there is no straightforward way to estimate the forces that it is producing other than (i) inserting a set of load cells underneath (which is rather invasive, but accurate), or (ii) estimating the force from the measured transfer function and measured response; this is only plausible if that source is the dominant source of vibration.

## 3. TRANSFER FUNCTION MEASUREMENTS

Although we conducted a few trial measurements at NRC Herzberg, the nature of the large equatorially mounted pier of the Plaskett 1.8m telescope is sufficiently dissimilar from large observatories on Maunakea that those results, while interesting, are not particularly relevant measurements for TMT. We were extremely fortunate to be given the opportunity to make transmissibility measurements at the Subaru Telescope in May of this year. A selection of those results are presented here.

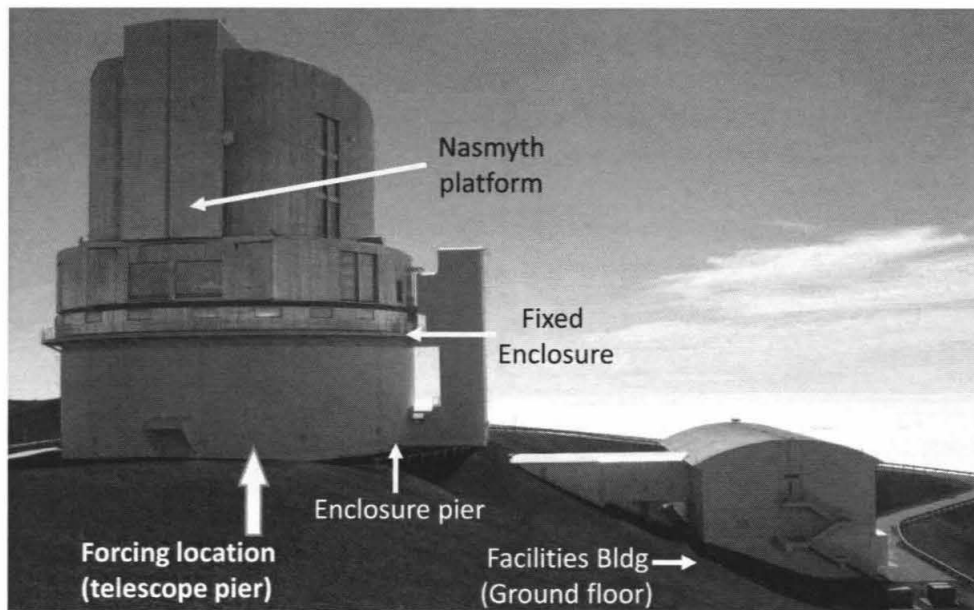


Figure 4. Subaru Observatory; forcing and response locations are indicated by the arrows.

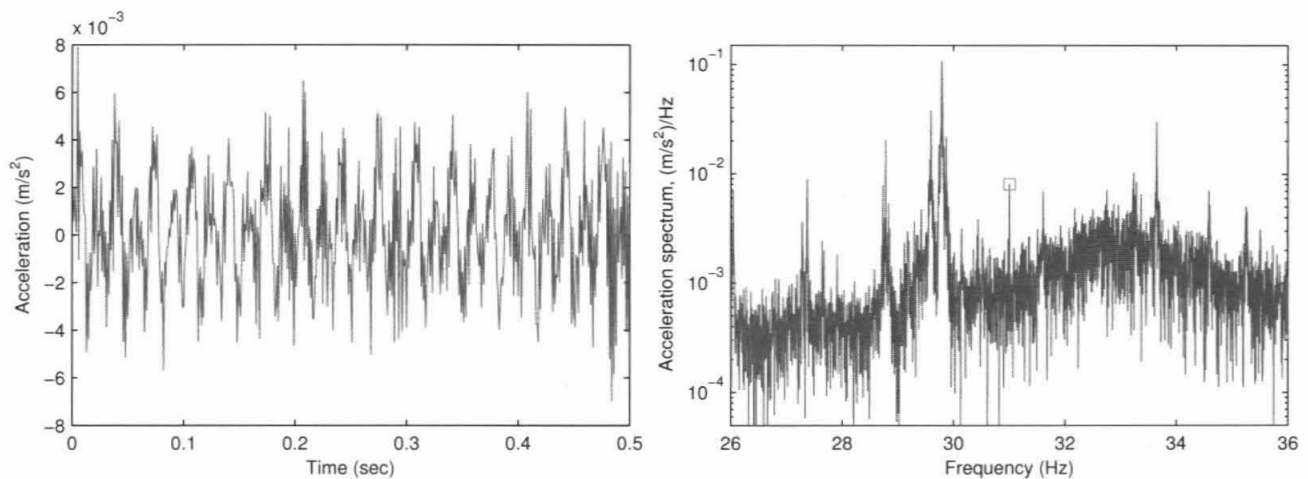


Figure 5. Example illustrating single-frequency forcing approach, showing the vertical response on the floor of the facilities building due to a 340 N force (241 N rms) applied at the telescope pier at 31 Hz. A typical time-domain plot is shown at left; the response at the drive frequency is not evident. However, in the narrow-band spectrum at right, the response is clear, with a signal-to-noise ratio of roughly 14 (determined as the height of the peak divided by the rms value over nearby frequency bins).

The source and response locations used at the Subaru observatory are shown in Figure 4. At each frequency, roughly 4 minutes of data were collected, and a single Fourier transform over the full 4 minute time window used to identify the response; this approach is illustrated in Figure 5.

The results are shown in Figure 6. The corresponding SNR is shown in Fig. 7. Excellent SNR is achieved at almost all frequencies; data points with  $\text{SNR} < 2$  are omitted in Fig. 6. The floor motion at the enclosure foundation is at least a factor of 5, and typically a factor of 10 times lower than the floor motion next to the shaker. Motion in the facilities building at Subaru is further reduced, at least a factor of 10 less than the nearby pier motion and typically a factor of 40-50. Note again that because of reciprocity this is equivalent to the relative motion at the telescope pier due to forces in the facilities building compared with pier forces; this is therefore directly relevant in establishing vibration budgets for TMT.<sup>1</sup>



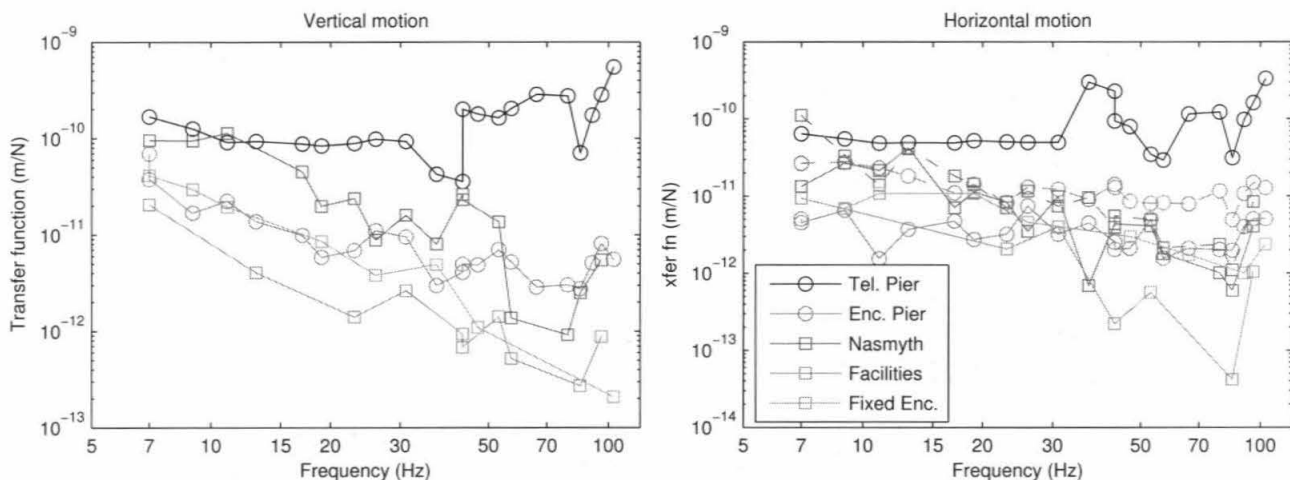


Figure 6. Transfer function at different locations, vertical (left) and horizontal motion (right). Only data points where the SNR is higher than two are included (Figure 7 includes all data points that were collected). Note that both 7 Hz and 43 Hz forcing was repeated for certain locations on two different days; it is not clear why the 43 Hz response differed at the same location; this may indicate a sensitivity to local details (e.g., due to a nearby resonance shifting slightly) or nonlinearity.

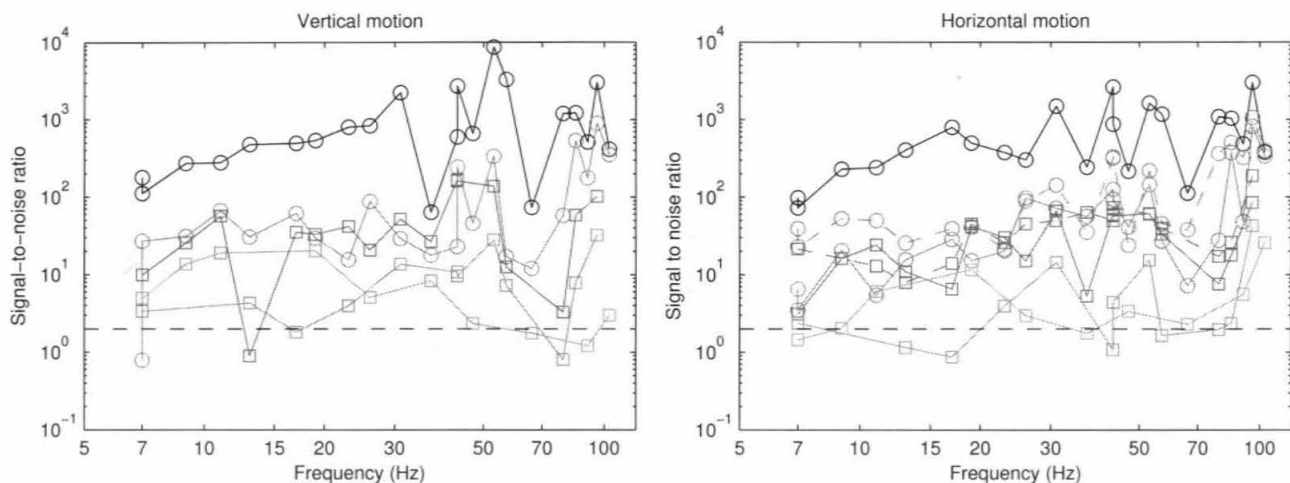


Figure 7. Signal to noise ratio corresponding to Figure 6; line-styles are the same. This is calculated as the ratio of the amplitude of the tone at the forcing frequency to the amplitude of the broadband background motion averaged over frequencies within  $\pm 1$  Hz (see Fig. 5). The SNR thus depends on the magnitude of the transfer function in Fig. 6, the background motion at the response location, the input force level, and the length of time over which the force is applied. Doubling the time results in double the frequency resolution and hence half the variance of broadband background motion per frequency-bin. The dashed line indicates an SNR of 2; points below this line were not included in Figure 6.

The transfer function was also measured from the pier input to the base of the fixed enclosure, on the rail where forces from the enclosure bogies are applied. Again, this transfer function ("Fixed Enc." in Fig. 6) is useful in estimating the relative impact of enclosure forces compared to pier forces. Up to roughly 40 Hz, the transfer function from this point to the telescope pier is similar to the transfer function from the enclosure foundation to the telescope pier; above 40 Hz there is additional attenuation due to the intervening structure.

While the preceding locations were primarily of interest for comparing the motion relative to the motion close to the applied force, the transfer function was also measured from pier forces to the Nasmyth platform. This is useful in understanding whether there is any structural amplification, and, more importantly, because this transfer function can also be computed from finite element models for comparison with the measured response.

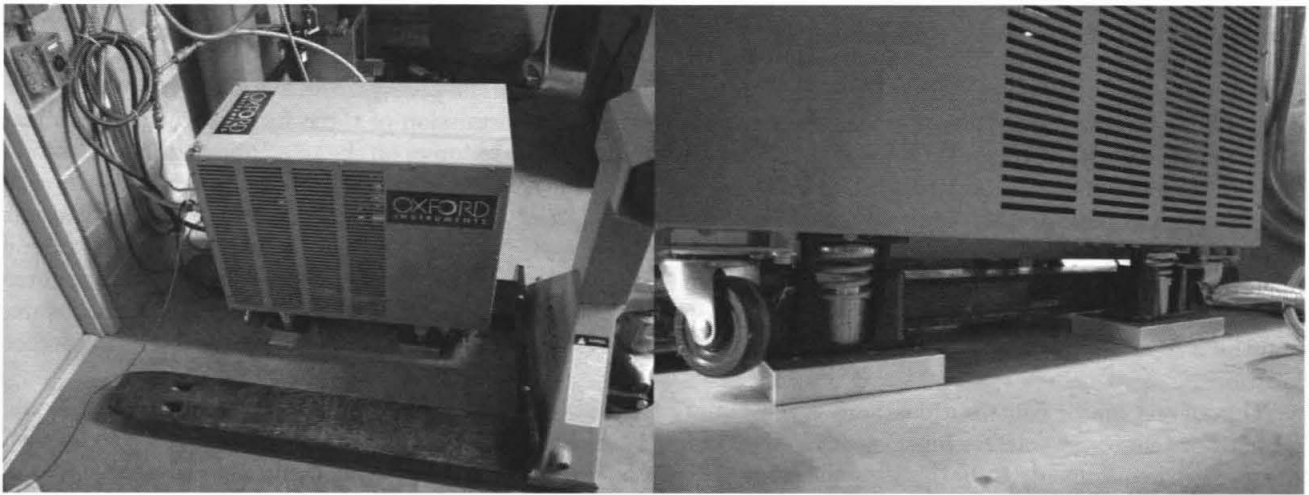


Figure 8. M600 Helium Compressor at NRC Herzberg used to demonstrate force measurement on isolators. Left-hand image shows compressor and jack used to raise the unit. Right-hand image shows isolators inserted under the compressor.

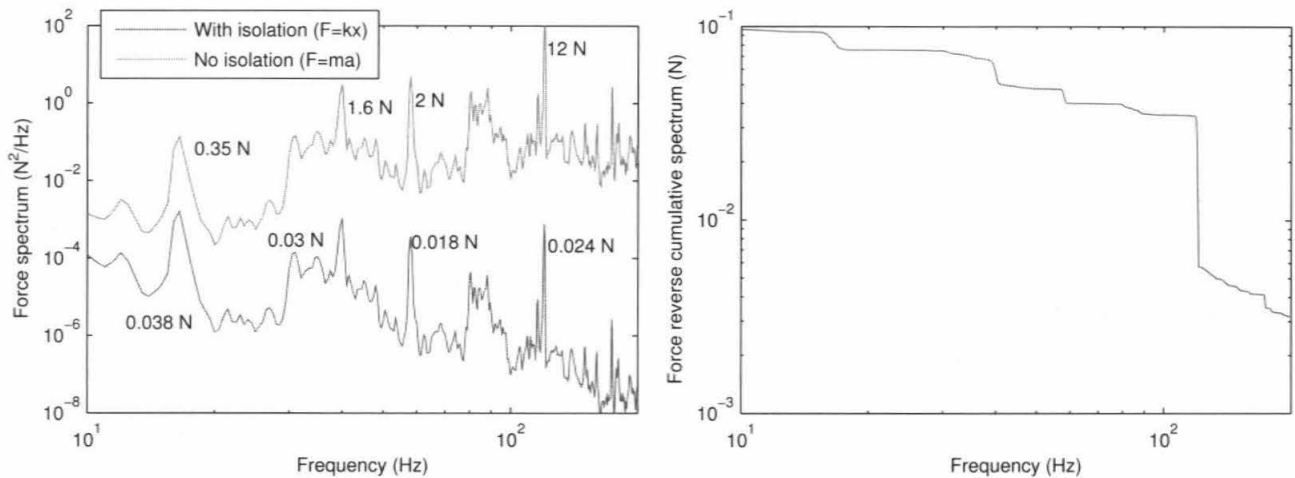


Figure 9. The left-hand plot shows the force spectra (with and without isolation) of the M600 Helium compressor. The right-hand plot shows the reverse cumulative number of Newtons over frequency for the isolated condition.

This is invaluable in building confidence in model-based sensitivity predictions that are being used as the basis for developing a vibration budget for TMT. Although the telescope, the soil stiffness, and pier design all differ, the comparable transfer functions magnitude is encouraging; see [1] for plots.

#### 4. FORCE MEASUREMENTS

A model M600 Helium compressor from Oxford Instruments at NRC Herzberg was used to demonstrate the method described in Section 2.2. The compressor was raised and mounted on four isolators as shown in Figure 8. The spring constants of the isolators are  $k = 18 \text{ kN/m}$  each; with a mass of 135.5 kg this yields an isolator frequency of 3.7 Hz. At any frequency well above this resonant frequency, the force transmitted through the isolation drops with the square of the frequency ratio (1), providing significant attenuation of forces.

A single three-axis accelerometer was used to measure the motion of the compressor in operation. The resulting estimated force spectrum for both what is transmitted to the base of the isolators and the force seen at the top of the isolators is shown in Figure 9.

## 5. CONCLUSIONS

Vibration due to equipment impacts adaptive optics performance at many observatories. However, while “best practices” engineering approaches have been employed, there has been limited quantitative data regarding either (i) the force levels produced by operating equipment, or (ii) the transmission of these forces through to optical performance. Models can be used to establish the optical response due to forces on the telescope or at the telescope pier, but require anchoring in data, and further, do not include the transmission of vibration disturbances through the ground and pier, despite many of the largest sources (in terms of force levels) being located in the summit facilities building. The data presented here represents the first ever quantitative measurements of its kind at any operating observatory, and helps to address this gap in knowledge. In particular, we have measured the force transmission from an applied force at the telescope pier to the response in the facilities building, the enclosure, and the Nasmyth platform; by reciprocity this also provides the telescope pier response to forces in these other locations.

One of the major contributions here is not simply the data itself, but the methodology both for collecting ground (or telescope) transfer functions despite low signal-to-noise ratio (SNR), and for estimating forces applied by operating equipment. In both cases, the estimates can be made without requiring equipment to be shut down, and thus has minimal interference to operations. The force transmission measurements are made with a single frequency input at a time; this allows the frequency to be chosen away from tones produced by equipment, allows high SNR (greater than 3 achieved for responses in the facilities building), and allows remote transfer function measurements to be made without cabling between them. The force levels produced by operating equipment can be estimated from the motion of the equipment and the isolator properties, as demonstrated here for a cryocompressor.

We hope that both the data and the methodology here will be broadly useful to the telescope community both for better understanding of the current vibration environment (and thus how best to allocate resources) and in the design of future observatories such as TMT.

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